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Physical Characteristics of Some Soils from the Middle East

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May 1992

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This report presents soil moisture and soil texture data on 59 soil samples from eastern Saudi Arabia, Iraq and Kuwait. Very little soil moisture data are available, and although the data reported here are probably overestimates, they are reported because of the apparent lack of such data. With respect to soil texture, the soils were grouped as sandy soils or gravelly soils, and then were further subdivided using a descriptive classification based on particle size differences. A modified version of the U.S. Department of Agriculture classification was used. This classification was tested using cluster analysis. Petrographic descriptions of 11 samples are included as an appendix. Although limited, the data are reported because of an apparent interest in such data with respect to military operations in desert areas.

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PREFACE

This report reflects one of the efforts conducted by TEC in support of Desert Shield/Desert Storm between August 1990 and April 1991. It was prepared under the supervision of Dr. J.N. Rinker, Senior Research Scientist, and of Mr. John V.E. Hansen, Director, Research Institute, in part under DA Project 4A161102B52C, Task FO, Work Unit 201, "Image Analysis Research."

Mr. Walter E. Boge was Director and COL Kenneth C. Kessler was Commander and Deputy Director of the Topographic Engineering Center at the time of publication of this report.

PHYSICAL CHARACTERISTICS OF SOME SOILS FROM THE MIDDLE EAST

INTRODUCTION

In September 1990 the Research Institute of the Topographic Engineering Center (TEC) initiated a feasibility study (Project Ostrich) to evaluate the usefulness of airborne long-wavelength (penetrating) radar to detect buried mines in soils comparable to those found in the Desert Shield area of operations in the Middle East. Work being done by TEC in conjunction with the U.S. Geological Survey near Yuma, Arizona, using airborne long-wavelength radars had shown images of what were believed to be subsurface objects, possibly buried ordnance (G.G. Schaber, U.S. Geological Survey, personal communication). Work done previously by McCauley et al. (1982), Blom et al. (1984), and McCauley et al. (1986), among others, indicated that one critical factor to success was the hyperarid nature of the soils where this work had been done. Hyperarid refers to soils that typically contain less than 1% soil moisture.

Project Ostrich involved building a minefield in soils comparable to those that occur in the Middle East: a site at the Marine Corps Air Ground Combat Center at Twentynine Palms, California was chosen. The major problem encountered with respect to soils was that very little information on the soils in the Desert Shield area of operations could be obtained, and what was available was not pertinent to the purposes of Project Ostrich. Data were needed so that the soil characteristics of the two areas could be compared. Several unsuccessful attempts were made to locate appropriate Army units and to obtain samples or data. Finally, a few samples were obtained from Mr. Ron Rhodes, U.S. Army Corps of Engineers Trans-Atlantic Division, from military personnel of the 529th Engineer Detachment stationed in Saudi Arabia, and from SSGT Michael Dibble (TEC), who spent several weeks in Saudi Arabia on temporary duty. Although this sampling was uncontrolled, all samples were gratefully accepted. The data on these samples is reported in Ehlen and Henley (1991).

Toward the end of Operation Desert Storm, samples were collected by Dr. J.N. Rinker (TEC), LTC Keith Wedge (U.S. Army Reserves), and Bob Knowles (U.S. Army Reserves and TEC). Although still not collected using a traditional sampling scheme, these samples were more useful because more information was provided with most of them. They also increased the total number of samples more than five times.

This report thus presents data on the physical characteristics of the 59 soil samples obtained from Saudi Arabia, Iraq and Kuwait in conjunction with Project Ostrich during Operations Desert Shield and Desert Storm. Soil samples came from eastern Saudi Arabia, from the Empty Quarter in the south to the northern border with Iraq and Kuwait; from the Neutral Zone between Saudi Arabia and Iraq; from western Kuwait; and from southern Iraq (Figure 1). Table 1 lists the samples by number and gives the latitude and longitude (determined primarily by military GPS) of their point of collection. Remarks provided by the individuals who collected the samples are also included where available. These remarks are somewhat cryptic, and are field descriptions. The country of origin is Saudi Arabia unless otherwise indicated. Samples 34 through 41 were too small to be evaluated by the procedures described in this report, although their locations are plotted on Figure 1.

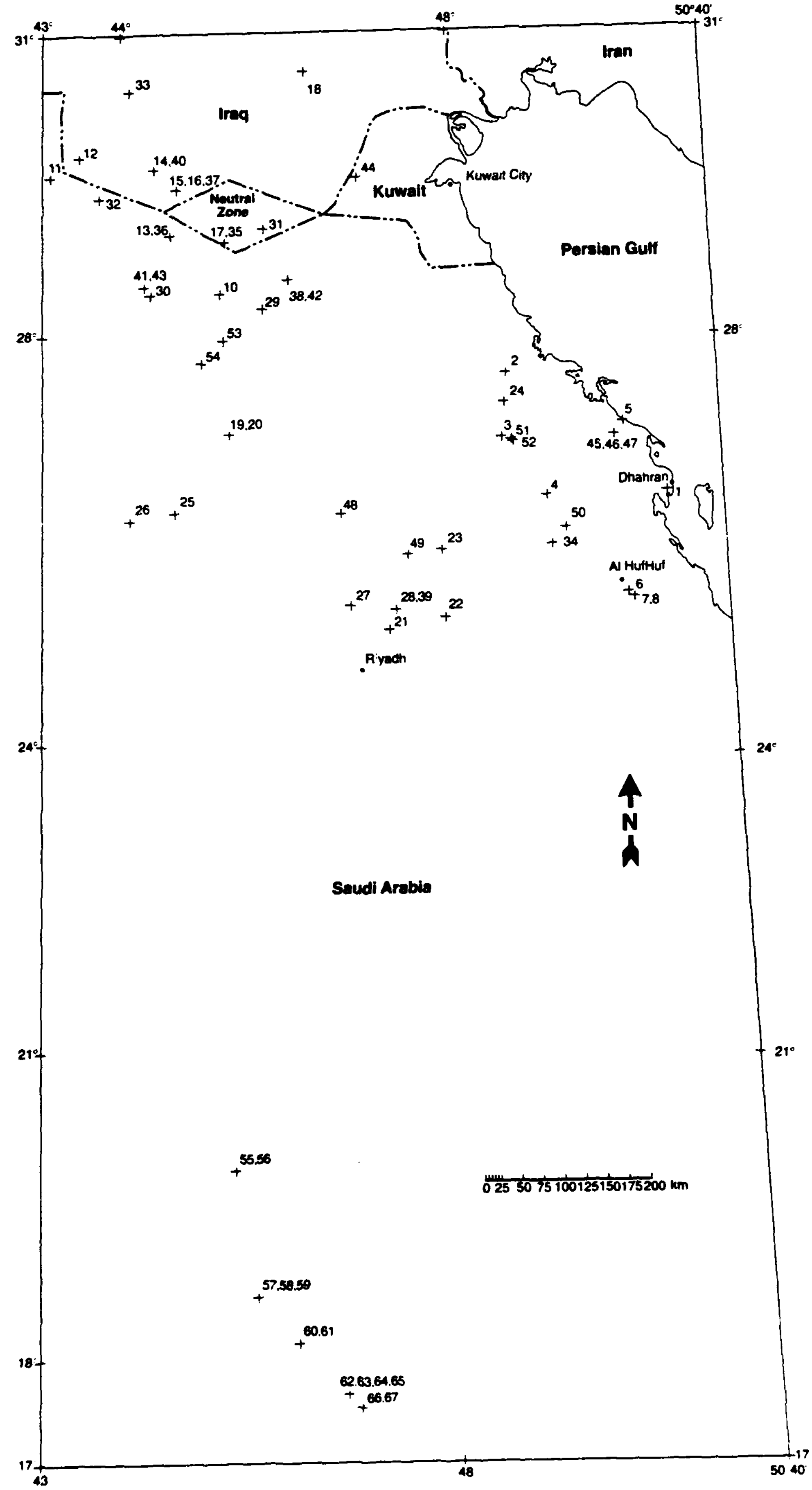

Figure 1. Map Showing Soil Sample Locations

Table 1. Latitudes, Longitudes and Descriptions of Samples

Sample Number	Latitude	Longitude	Field description/Remarks[1]
SA-1	26°14.4'N	50°9.7'E	
SA-2	27°29'N	48°27'E	
SA-3	26°52'N	48°22'E	
SA-4	26°16'N	48°50'E	
SA-5	26°55'59"N	49°42'52"E	~ 140 km south of Kuwait, 500m inland from the Gulf Coast
SA-6	25°17'00"N	49°38'45"E	
SA-7	25°13'00"N	49°41'15"E	
SA-8	25°12'30"N	49°42'30"E	
SA-9			
SA-10	28°23'N	45°20'E	
SA-11	29°33'N	43°28'05"E	subsurface, material from up to 10-15 cm depth
SA-12	29°44.1'N	43°48'E	gravel/duricrust (Iraq)
SA-13	28°58'N	44°48'E	silty sand, Karma domes swale
SA-14	29°36.7'N	44°38.1'E	sand (Iraq)
SA-15	29°24'N	44°53'E	duricrust (Iraq)
SA-16	29°24'N	44°53'E	silt flat (Iraq)
SA-17	28°53'N	45°24'E	bulk, Wadi Batin
SA-18	30°31.3'N	46°23.0'E	barchan dune area, interdune flat (Iraq)
SA-19	27°00.5'N	45°23.0'E	top of dune, Ad Dahna sandsheet, 12 km N of Um al Jamajim
SA-20	27°00.5'N	45°23.0'E	swale, Ad Dahna sand sheet, 12 km N of Um al Jamajim
SA-21	25°03'N	47°02'E	duricrust escarpment
SA-22	25°08.2'N	47°39'E	dune crest, Ad Dahna sandsheet
SA-23	25°48'N	47°39'E	bulk
SA-24	27°11.6'N	48°25.0'E	sand quarry
SA-25	26°15.5'N	44°43.3'E	dome dune, Ad Dahna sandsheet
SA-26	26°11.7'N	44°15'E	Ad Dahna sandsheet
SA-27	25°18'N	46°38'E	
SA-28	25°13.5'N	47°07.2'E	bulk, silt flat
SA-29	28°13.0'N	45°48.0'E	wadi
SA-30	28°23.26'N	44°32.57'E	
SA-31	29°0.04'N	45°51.45'E	
SA-32	29°20'N	44°01.6'E	
SA-33	30°23.03'N	44°23.2'E	Iraq
SA-42	28°30'N	46°06.2'E	bulk, western bank, Wadi Batin
SA-43	28°27.9'N	44°28.7'E	bulk, wadi area
SA-44	29°27'N	46°56'E	Kuwait

[1] Unless stated otherwise, country of origin is Saudi Arabia.

Table 1. (continued)

Sample Number	Latitude	Longitude	Field description/Remarks[2]
SA-45	26°49'N	49°36.5'E	sahbka
SA-46	26°49'N	49°36.5'E	sahbka, bulk, top 5 cm
SA-47	26°49'N	49°36.5'E	sahbka, 1st hard layer
SA-48	26°12'N	46°35'E	campsite, Ad Dahna sandsheet
SA-49	25°46.0'N	47°17.3'E	
SA-50	25°56.6'N	49°01.2'E	
SA-51	26°49.5'N	48°28.4'E	
SA-52	26°49.0'N	48°28.7'E	
SA-53	27°55.88'N	45°20.75'E	
SA-54	27°43.02'N	45°05.69'E	
SA-55	19°48.88'N	45°07.97'E	Empty Quarter
SA-56	19°48.88'N	45°07.97'E	4" deep (Empty Quarter)
SA-57	18°35.26'N	45°18.90'E	Empty Quarter
SA-58	18°35.26'N	45°18.90'E	2-4" deep (Empty Quarter)
SA-59	18°35.26'N	45°18.90'E	Empty Quarter
SA-60	18°07.27'N	45°43.76'E	Empty Quarter
SA-61	18°07.27'N	45°43.76'E	subsurface (Empty Quarter)
SA-62	17°35.49'N	46°12.77'E	dune crest (Empty Quarter)
SA-63	17°35.49'N	46°12.77'E	interdune troughs (Empty Quarter)
SA-64	17°35.50'N	46°12.77'E	dune surface, windward (Empty Quarter)
SA-65	17°35.50'N	46°12.77'E	dune subsurface, windward, S side (Empty Quarter)
SA-66	17°28.19'N	46°20.79'E	interdunal area (Empty Quarter)
SA-67	17°28.19'N	46°20.79'E	subsurface, interdunal area (Empty Quarter)

Very little information was provided regarding the depth from which the samples were collected. Most descriptions are "surface," "subsurface" or "bulk" with no depths given.[3] For 46 samples with such descriptors, 33 are surface samples and 13 are from the subsurface. Surface samples were collected mainly by taking a handful of soil from the surface, probably no deeper than 4 cm. Most of the subsurface, or bulk, samples were apparently collected from 5-10 cm depths; the deepest samples extend to depths of 15 cm. Unless described as "bulk" or "subsurface" in Table 1, all samples are surface samples (i.e. 0-4 cm).

[2] Unless stated otherwise, country of origin is Saudi Arabia.

[3] "Bulk" refers to a sample collected from the subsurface (J.N. Rinker, U.S. Army Topographic Engineering Center, oral communication, 1992).

In addition to soil texture, spectral reflectance curves for samples SA-1 through SA-8 were reported by Ehlen and Henley (1991). Information on the thermal infrared characteristics of these soils as well as some rock samples from the same area can be found in Eastes (in prep). Petrographic data on selected samples are given in Appendix A (Rubick Luttrell, 1991a and 1991b).

The data presented below are limited because (1) no controlled sampling scheme was used, (2) very few samples were collected over a very large area and (3) many samples are random grab samples, collected by individuals with limited knowledge of soil characteristics. An attempt has been made, however, to group the soils statistically according to particle-size characteristics.

Soil Moisture

As stated above, soil moisture was a primary concern in choosing a test site for Project Ostrich Hansen et al., in prep). Soil moisture was measured on soils from the test site, but only one reference to soil moisture in the area of interest (Berlin et al., 1986) was located in the literature; no other source of such data was found. Berlin et al. (1986) report soil moisture in the Al Labbah sand in northern Saudi Arabia to be 0.148-0.248% at 20-30 cm depth and 0.183-0.578% at 50 cm depth. Surface soil moisture was reported as ranging from 0.054% to 0.077%.

Soil moisture was not determined for most of the samples listed in Table 1. None of the samples were weighed in the field and sample history after collection was not known. Soil moisture was determined on five samples that appeared to have been collected under more controlled conditions. The results are reported here, because of the apparent lack of such information in the literature, although they probably don't represent the actual soil moisture conditions when the samples were collected. These soil moisture values are about one magnitude greater than those reported by Berlin et al. (1986).

Upon receipt, the soil samples were weighed, then oven dried to constant weight at 103° C. Drying to constant weight usually took 36-48 hours. Soil moisture was then calculated on an oven-dry weight basis.

Soil moisture was determined for samples SA-2, SA-3 and SA-4, which are surface samples (0-4 cm depth). Soil moisture for these sample was 0.58%, 13.3% and 0.38%, respectively. Soil moisture for sample SA-3 is particularly high due to the presence of a large amount of gypsum, a hydrated mineral. Water of hydration as well as free water is driven off during heating.

Soil moisture was also determined for samples SA-10 (0-4 cm depth) and SA-11 (10-15 cm depth), collected during the rainy season. Containers for these samples were sealed with tape and their transit time was not long. Soil moisture in these two samples was 1.8% and 3.7%, respectively. These values compare well with those for samples SA-2 and SA-4 when climatic conditions are taken into consideration.

Soil Texture

Procedures

Particle-size analysis was performed on the 59 oven-dried samples. The samples were weighed and then sieved. After sieving, the individual separates were weighed so that their proportion of the total could be determined. A modified U.S. Department of Agriculture classification (U.S.D.A., 1951) was used: gravel (>2 mm), very coarse sand (1-2 mm), coarse sand (0.5-1 m), medium sand (0.25-0.5 mm), fine sand (0.125-0.25 mm), very fine sand (0.075-0.125 mm), and silt+clay (<0.075 mm). Sieve sizes for each of these fractions are: No. 10, No. 18, No. 35, No. 60, No. 120 and No. 200, respectively. An agricultural classification was used, rather than the Unified Classification, because agricultural classifications contain more fractions in the sand category, the category of greatest interest.

Sieve Analysis

Table 2 lists soils classified as sandy, i.e. soils containing less than 20% gravel-sized particles. Table 3 shows soils classified as gravelly, i.e. soils containing more than 20% gravel-sized particles. Figures in parentheses at the bottom of columns in the tables are means for each sieve separate. Figures 2 and 3 show graphically the distribution of the sieve separates for sandy and gravelly soils, respectively.

Sandy Soils. Thirty-six samples are classed as sandy soils. Sample SA-1 is excluded from the calculation of means on Table 2 because the amount of the >2 mm fraction was not determined. Of the remaining 35 sandy soils, 5 are classified as fine sands (14.3%), 14 as sands (40.0%), 11 as coarse sands (31.4%), 3 as loamy sands (8.6%), 1 as loamy coarse sand (2.8%), and 1 as sandy loam (2.8%). Means for the separates of these samples are: 0.6% gravel, 4.6% very coarse sand, 14.5% coarse sand, 26.9% medium sand, 42.3% fine sand, 9.1% very fine sand, and 2.3% silt+clay.

Because of their appearances, textures and field descriptions, 14 samples (SA-9, 19, 22, 24, 25, 27, 50, 54, 55, 56, 62, 63, 64, and 65) were considered dune sands. Means for the separates of these samples are: 4.6% gravel, 5.4% very coarse sand, 14.8% coarse sand, 27.5% medium sand, 32.9% fine sand, 10.9% very fine sand, and 4.8% silt+clay.

Gravelly Soils. Of the 23 gravelly soils, 15 are gravelly sand (65.2%) and 8 are gravelly loamy sand (34.8%). Although classed as gravelly, sample SA-47 may be anomalous: it comes from the first hard layer below the surface of a sahbka. In this sample, particles >2 mm in size consist of cemented sand grains and are thus not true gravel particles. Means for gravelly soils are 33.0% gravel, 8.3% very coarse sand, 9.3% coarse sand, 13.6% medium sand, 17.3% fine sand, 10.5% very fine sand, and 8.1% silt+clay.

Classification

Cluster analysis was chosen to evaluate the traditional soil classification discussed above and shown in Tables 2 and 3 because it offers an objective and unbiased approach to the grouping of similar objects. The clustering routine used, Ward's Method, is an hierarchical, agglomerative classification. Ward's Method chooses two clusters at each step, initially two data points, the combination of which leads to the least increase in the euclidean sum of squares, a distance measure calculated from a similarity matrix. As clustering proceeds, the number of clusters is reduced, e.g. in this case, from 58 to 1.[4]

[4] Sample SA-1 was not included in the cluster analysis because the weight of the >2 mm separate is unknown.

Table 2. Particle Size, Sandy Soils

Sample Number	>2mm	1-2mm	0.5-1 mm	0.25-0.5mm	0.125-0.25mm	0.075-0.125mm	<0.075 mm	Description
SA-22	0.0	0.0	0.0	44.4	50.6	5.0	0.0	fine sand
SA-25	0.0	0.0	0.0	18.0	72.7	8.8	0.5	fine sand
SA-63	0.0	0.1	0.8	21.4	70.2	6.9	0.5	fine sand
SA-64	0.0	0.0	0.0	1.9	83.6	12.5	2.0	fine sand
SA-65	0.0	0.0	0.0	1.7	86.7	10.7	0.8	fine sand
(mean)	(0.0)	(0.0)	(0.2)	(17.5)	(72.8)	(8.8)	(0.8)	
SA-4	3.2	0.3	12.2	34.9	33.2	11.0	5.3	sand
SA-5	14.0	5.0	15.9	32.0	20.5	5.9	6.7	sand
SA-9	0.0	0.0	0.0	54.2	42.1	3.7	0.0	sand
SA-12	1.6	0.7	16.5	31.3	33.4	12.9	3.6	sand
SA-19	0.0	0.0	tr	49.3	46.8	3.7	0.3	sand
SA-20	0.0	tr	5.2	45.1	45.1	4.3	0.3	sand
SA-26	tr	1.9	17.0	37.3	32.1	10.4	1.3	sand
SA-28	5.2	7.0	8.7	10.5	36.5	24.7	7.4	sand
SA-31	17.1	4.6	10.4	32.2	20.7	10.6	4.3	sand
SA-42	19.4	10.3	13.6	26.8	17.1	7.4	5.5	sand
SA-46	0.9	1.3	18.9	42.8	25.9	6.9	3.3	sand
SA-48	0.0	0.5	18.5	30.2	44.1	5.2	1.5	sand
SA-54	0.5	tr	9.8	38.3	39.8	8.7	2.8	sand
SA-67	1.8	5.3	12.7	38.4	27.5	9.8	4.5	sand
(mean)	(4.6)	(2.6)	(11.4)	(36.0)	(31.0)	(8.9)	(3.3)	
SA-43	17.1	7.7	11.1	15.9	13.6	13.5	21.1	sandy loam
SA-1	na	10.7	13.8	19.3	27.8	14.7	13.7	loamy sand
SA-30	10.0	4.1	9.5	20.2	28.4	14.8	13.1	loamy sand
SA-33	18.8	10.6	10.4	13.0	14.1	15.6	17.6	loamy sand
SA-66	15.3	10.4	12.6	13.9	16.1	17.7	14.1	loamy sand
(mean)	(14.7)	(8.4)	(10.8)	(15.7)	(19.5)	(16.0)	(14.9)	
SA-15	10.0	10.5	15.5	22.1	20.1	10.9	10.8	loamy coarse sand
SA-2	1.3	13.4	13.3	32.8	26.7	9.0	3.4	coarse sand
SA-6	4.7	19.3	16.4	21.8	19.2	11.3	7.3	coarse sand
SA-17	13.2	8.6	21.5	29.5	18.5	6.0	2.6	coarse sand
SA-18	0.0	0.4	29.4	17.6	46.1	6.1	0.5	coarse sand
SA-24	1.0	1.5	25.4	60.2	10.9	0.5	0.4	coarse sand
SA-27	0.1	4.3	22.0	20.1	31.6	18.0	4.0	coarse sand
SA-45	0.6	1.7	24.8	39.4	21.7	9.6	2.3	coarse sand
SA-50	0.0	tr	27.9	32.0	24.5	11.5	4.1	coarse sand
SA-55	5.7	30.4	18.8	11.7	14.1	14.3	5.1	coarse sand
SA-56	1.1	17.2	24.4	12.2	13.7	22.5	8.8	coarse sand
SA-62	0.0	10.2	74.4	11.1	4.2	0.2	0.0	coarse sand
(mean)	(2.5)	(9.7)	(27.1)	(26.2)	(21.0)	(9.9)	(3.5)	

Table 3. Particle Size, Gravelly Soils

Sample Number	>2mm	1-2mm mm	0.5-1 0.5mm	0.25- 0.25mm	0.125- 0.125mm	0.075- mm	<0.075	Description
SA-10	25.1	7.4	9.2	14.8	20.7	12.6	10.1	gravelly loamy sand
SA-11	46.9	10.0	9.1	8.2	7.8	7.2	10.9	gravelly loamy sand
SA-13	24.8	8.9	9.8	14.5	15.8	10.6	15.5	gravelly loamy sand
SA-14	20.2	7.1	9.0	14.0	17.9	15.6	16.2	gravelly loamy sand
SA-16	25.9	10.6	11.1	12.5	12.5	10.4	17.0	gravelly loamy sand
SA-29	27.7	11.4	8.6	14.2	16.6	9.7	11.8	gravelly loamy sand
SA-32	22.8	10.1	10.5	14.6	20.3	11.3	10.4	gravelly loamy sand
SA-60	42.3	5.7	1.0	2.3	22.3	16.3	10.2	gravelly loamy sand
(mean)	(29.5)	(8.9)	(8.5)	(11.9)	(16.7)	(11.7)	(12.8)	
SA-3	22.0	16.0	14.7	16.7	17.8	8.0	4.7	gravelly sand
SA-7	31.7	6.5	8.6	15.4	18.8	13.6	5.3	gravelly sand
SA-8	27.1	4.7	10.6	16.3	18.5	15.4	7.5	gravelly sand
SA-21	37.2	5.3	11.2	14.5	18.8	8.9	4.1	gravelly sand
SA-23	20.5	12.1	13.2	14.1	18.8	13.2	8.3	gravelly sand
SA-44	36.5	7.9	9.8	15.3	16.6	9.5	4.4	gravelly sand
SA-47	52.3	2.4	5.4	19.9	13.0	6.3	0.6	very gravelly sand
SA-49	30.1	7.3	7.4	15.8	24.7	8.9	5.8	gravelly sand
SA-51	28.8	9.4	8.3	10.4	21.9	12.7	8.4	gravelly sand
SA-52	55.4	11.8	7.2	7.7	9.6	5.1	3.3	gravelly sand
SA-53	22.5	12.5	12.6	13.3	19.7	10.5	8.8	gravelly sand
SA-57	36.6	6.6	7.4	15.3	20.8	9.1	4.2	gravelly sand
SA-58	42.7	7.6	7.7	11.8	14.7	7.7	7.9	gravelly sand
SA-59	61.0	4.7	14.6	14.2	3.7	1.1	0.7	gravelly sand
SA-61	19.6	5.1	7.0	16.0	26.0	16.8	9.4	gravelly sand
(mean)	(34.9)	(8.0)	(9.7)	(14.4)	(17.6)	(9.8)	(5.6)	

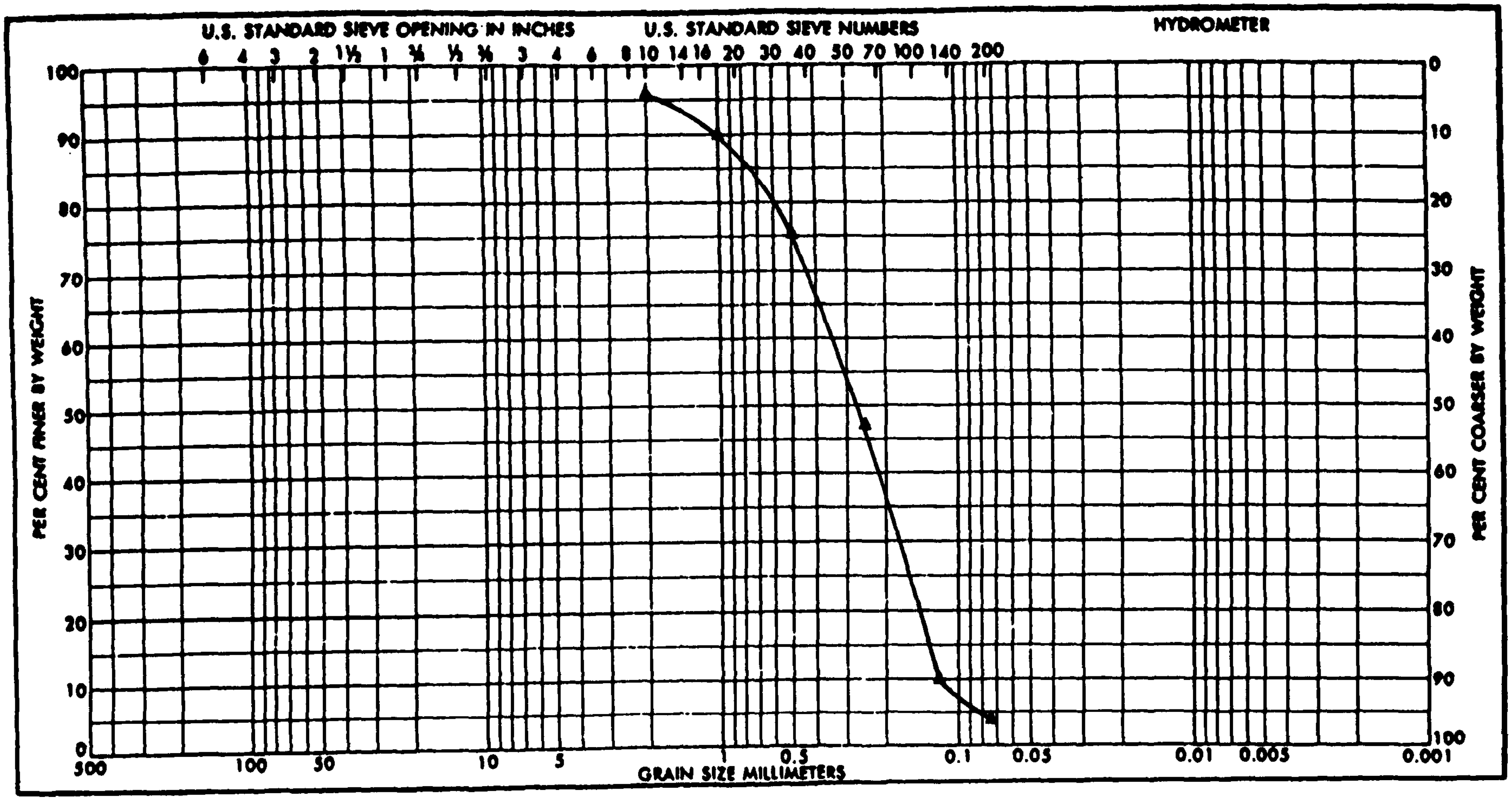

Figure 2. Sieve Separate Distributions, Sandy Soils

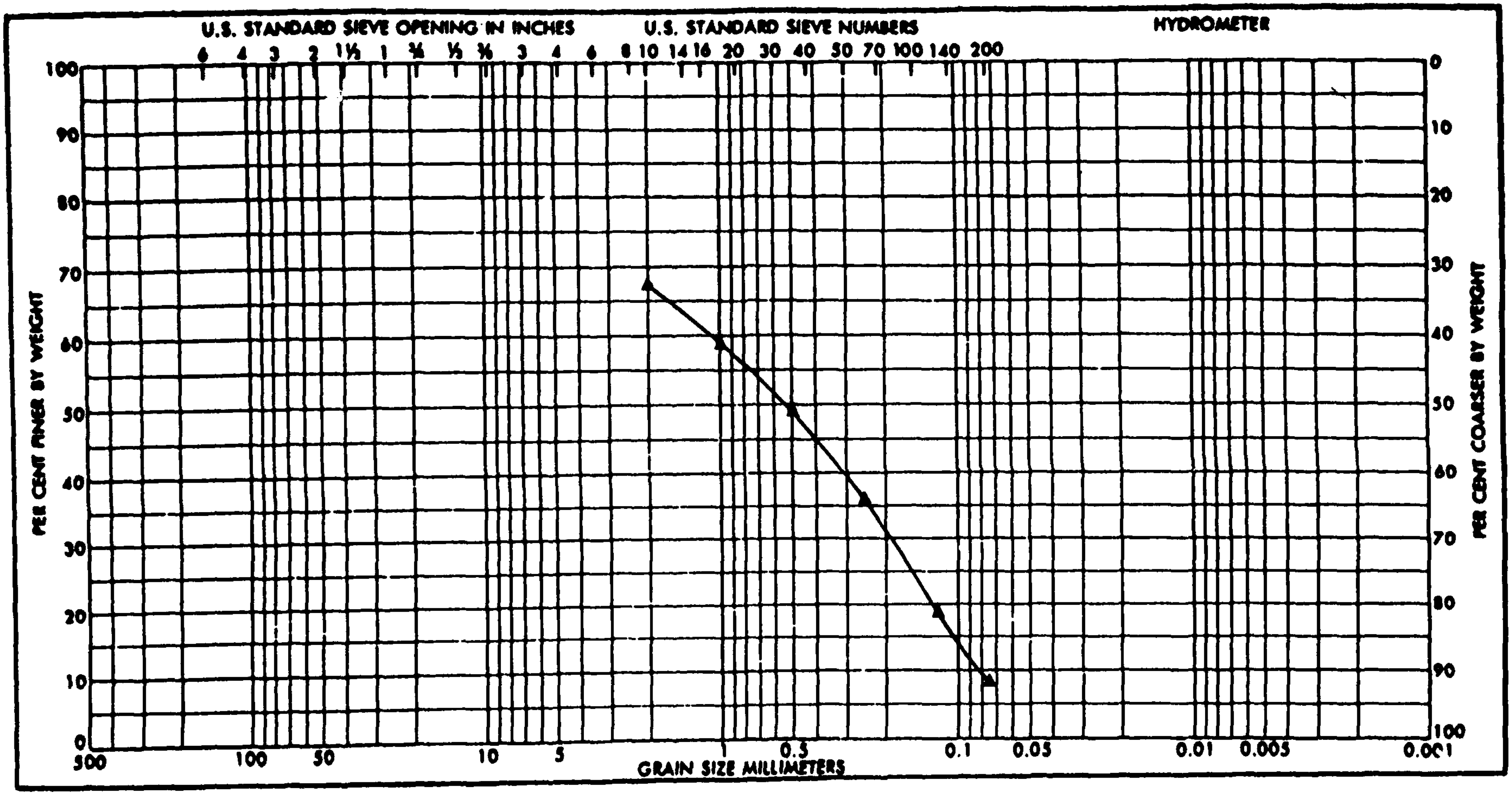

Figure 3. Sieve Separate Distributions, Gravelly Soils

Each clustering routine produces a "best" classification for a given number of clusters, which is chosen by the user. For instance, if the user wishes four clustering levels, the program will produce the most distinct combinations for groups of four, three, two and one clusters. "Best" is defined in terms of the clustering algorithm; if a distance measure is used as in this case, "best" would be the smallest or largest distance between members of a given cluster and the greatest or least distance between clusters depending on the type of coefficient used. The coefficient used in this analysis was a dissimilarity coefficient, so the greatest distance was calculated. The most appropriate, or best, clustering level is often determined by identifying multiple clusters with similar clustering coefficients (as shown on the y axis) directly from the dendrograms (see Figure 4). The line a-b above and parallel to the x axis indicates the best clustering level for this classification, the four-cluster level (four tie-lines are crossed). There is seldom an obvious "best" for any clustering routine and, consequently, two or three groups of clusters are often evaluated.

In this case, ten clustering levels were evaluated, and levels consisting of two and five clusters were considered best. The level containing eight clusters, the number of different soil textures shown in Tables 2 and 3, was considered worst, ranking 10 out of 10.

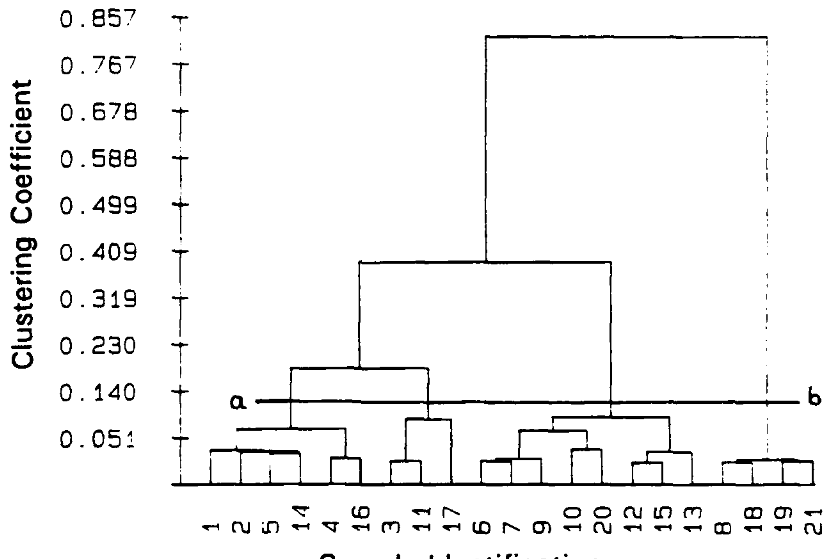

Figure 4. Typical Dendrogram. Line a-b indicates the optimum clustering level, the four-cluster level

Two-Cluster Classification. This classification does not separate samples described as sandy soils (Table 2) from those described as gravelly soils (Table 3) as had been hoped, but it does very successfully separate the finer- from the coarser-textured soils. Cluster 1, which represents the coarse-textured soils, contains all those soils described as loamy or gravelly in addition to 63.6% of the coarse sands and 28.6% of the sands. There are no fine sands in this cluster. Most subsurface samples are in Cluster 1. Cluster 2, which represents the fine-textured soils, contains all the fine sands, 71.4% of the sand soils, and 36.4% of the coarse sands. Table 4 shows the soil samples in each cluster.

With respect to spatial pattern, the samples in Cluster 1 occur throughout the area in which the samples were collected. Those in Cluster 2, however, tend to occur primarily in the central part of the area, below latitude 28° and above latitude 25°.

Table 4. Soil Sample Distribution in the Two-Cluster Classification

Cluster 1:				Cluster 2:	
SA-2	SA-15	SA-32	SA-55	SA-4	SA-45
SA-3	SA-16	SA-33	SA-56	SA-9	SA-46
SA-5	SA-17	SA-42	SA-57	SA-12	SA-48
SA-6	SA-21	SA-43	SA-58	SA-18	SA-50
SA-7	SA-23	SA-44	SA-59	SA-19	SA-54
SA-8	SA-27	SA-47	SA-60	SA-20	SA-63
SA-10	SA-28	SA-49	SA-61	SA-22	SA-64
SA-11	SA-29	SA-51	SA-62	SA-24	SA-65
SA-13	SA-30	SA-52	SA-66	SA-25	SA-67
SA-14	SA-31	SA-53		SA-26	

Five-cluster classification. This classification predictably allows more differentiation than the two-cluster classification. Surface and subsurface samples are relatively evenly distributed throughout the five clusters. The distribution of soil samples among the clusters is shown in Table 5.

Cluster 1 contains 64% of the samples described as coarse sand in Table 2 as well as the one loamy coarse sand and 29% of the sands, but only 7% of the gravelly sands; the soils is Cluster 1 can be called *gravelly coarse sands*. Most of these samples have very large very coarse sand (1-2 mm) separates compared to other members of their soil texture groups. Silt+clay separates (<0.075 mm) tend to be large as well. The sand soils in this cluster also have very large gravel components (>2 mm). Cluster 1 contains the largest proportion of subsurface samples; depth of sampling is known for 85% of the samples in the cluster. The samples in Cluster 1 exhibit no spatial pattern, although they tend to be most common in the central area, nearer to Persian Gulf, east of longitude 46°, between 25° and 28° latitude.

Cluster 2 consists primarily of sand soils with coarse sand soils and one fine sand soil; the soils in this cluster can be called *sands*. The coarse sand soils have very low percentages of gravel (>2 mm), very coarse sand (1-2 mm), and very fine sand (0.075-0.125 mm). This cluster includes 71% of the sand soils shown in Table 2 as well as 36% of the coarse sands. In addition, it contains the highest proportion of surface samples, but depth of sampling is known for only 75%. Most Cluster 2 samples occur in an east-west band between latitudes 25° and 28°.

Cluster 3 soils, which consist of gravelly sand and gravelly loamy sand, can be called *gravelly sands*. Gravelly sands comprise 83% of Cluster 3, and 67% of the gravelly sands occur in Cluster 3. Compared to the gravelly loamy sands in other clusters, the gravelly loamy sands in Cluster 3 have very large gravel separates (>2 mm), large very coarse sand separates (1-2 mm), very small coarse and medium sand separates (0.5-1 mm and 0.25-0.5 mm, respectively), and small silt+clay separates

(<0.075 mm). Twenty-five percent of the gravelly loamy sand soils shown in Table 3 are in Cluster 3. Cluster 3 samples occur through the collecting area.

Table 5. Soil Sample Distribution in the Five-Cluster Classification

Cluster: 1	2	3	4	5
SA-2	SA-4	SA-7	SA-9	SA-10
SA-3	SA-12	SA-8	SA-19	SA-13
SA-5	SA-18	SA-11	SA-20	SA-14
SA-6	SA-26	SA-21	SA-22	SA-16
SA-15	SA-45	SA-44	SA-24	SA-23
SA-17	SA-46	SA-47		SA-29
SA-30	SA-48	SA-49		SA-30
SA-31	SA-50	SA-52		SA-32
	SA-54	SA-57		SA-33
	SA-67	SA-58		SA-43
		SA-59		SA-51
		SA-60		SA-53
				SA-61
				SA-63

Cluster 4 consists primarily of loamy soils (gravelly loamy sands, loamy sands and sandy loam), but also contains some gravelly sands; the soils in this cluster can be called *gravelly and loamy sands.* More than 70% of the loamy soils are in Cluster 4. These soil samples are low in gravel (>2 mm), compared to other members of their soil texture groups, and contain relatively large amounts of all separates but medium sand (0.25-0.5 mm). This cluster includes 75% of the gravelly loamy sands and 27% of the gravelly sands listed in Table 3. With respect to spatial pattern, most samples in Cluster 4 occur in the northwest part of the collecting area, west of longitude 46° and north of latitude 28°.

Cluster 5 contains only fine sand soils, and can therefore be called *fine sands*. Eighty percent of the fine sand soils shown in Table 2 are included in the cluster. These four samples are distinguished from the fifth fine sand (SA-22) by having smaller medium sand separates (0.25-0.5 mm), and larger fine sand and very fine sand separates (0.125-0.25 mm and 0.075-0.125 mm, respectively). In addition, these four samples contain at least small amounts of silt+clay (<0.075 mm), whereas the remaining sample contains none. All but one of these samples are surface samples; the sampling depths are known. Three of the four samples came from the Empty Quarter in Saudi Arabia.

Viewing the classification from another perspective, most of the soil types listed in Tables 2 and 3 occur primarily in one cluster. Cluster 1 contains 64% of the coarse sands; 71% of the sands are in Cluster 2; 67% of the gravelly sands are in Cluster 3; 75% of the gravelly loamy sands are in Cluster 4; and Cluster 5 contains 80% of the fine sands. The loamy sand, loamy coarse sand and sandy loam soils occur in one cluster. Gravelly sands are the only soil texture group that occurs in more than two clusters.

Conclusions

Over the past two years, a number of requests for these data have been received from various government agencies (e.g. Department of Energy, Department of Army, and other elements of the Defense Department), from contractors working for these agencies, and from universities. Their interests centered around the effects of soils of the Middle East on the operation and maintenance of military equipment and they had been unable to locate data on soils in the Middle East. Because data on the physcial characteristics of Middle East soils is very difficult to obtain, the above data on these 59 soils, although limited, will prove useful to others as well.

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Appendix A

PETROGRAPHIC ANALYSIS

Eleven samples were sent to Patty Rubick Luttrell, a professional consulting geologist, for petrographic analysis. Her descriptions and the results of her analyses comprise this appendix, in which a geologic particle-size classification was used. Particle-size ranges for the particle names used, therefore, do not necessarily agree with those used in the body of this report. Color photomicrographs to facilitate sample descriptions of the thin sections were included in the unpublished contract report, but are not reproduced here.

Methodology

Sample texture and composition were determined by thin section analysis. Thin sections were made by mounting loose grains with epoxy. Slides were stained with sodium cobaltinitrite to facilitate the identification of potassic feldspar and Alizarin red-S to differentiate dolomite from calcite.

Sample Descriptions

Samples examined ranged in grain size from granule (2.25-2.00 mm) to sand (1.75-0.27 mm) to silt (0.06-0.002 mm) to mud (2/3 silt, 1/3 clay) to clay ($<2\ \mu$). The samples are assigned a compositional name based on grain size and composition (Folk, 1974).

Sample SA-1:

A light buff, moderately to poorly sorted, subrounded, fine-grained (0.24 mm) *sand* collected west of Dhahran. A thin film of detrital calcite ($CaCO_3$) cement coats the majority of grains.

The sand composition consists of quartz (30%), feldspar/plagioclase (<1%), carbonate rock fragments (54%), gypsum rock fragments (15%), sandstone rock fragments (1%), chert (<1%), plutonic rock fragments (<1%), mica (<1%) and <1% heavy minerals (magnetite, zircon). The sample is classified as a *gypsiferous quartzose carbonate lithic arenite* (15% gypsum, 30% quartz, 1% sandstone rock fragments, 54% carbonate rock fragments).

The carbonate rock fragments are micritic (microcrystalline) to sparry (coarsely crystalline) and are the dominant lithic in this sample (54%). Some of the carbonate rock fragments contain fossils (trilobites, echinoderms) which document the rock fragments as being marine in origin. After cementation, the carbonate was eroded and transported as discrete sand-sized grains.

The gypsum ($CaSO_4 2H_2 0$) rock fragments are the second most abundant lithic. The gypsum shows partial replacement by calcite ($CaCO_3$) as well as detrital calcite cement along the outer rim of the grains.

The composition of this sand indicates a mixed parentage of sedimentary and plutonic terrain. Evidence for a sedimentary input involves quartz, reworked quartz overgrowths, carbonate rock fragments of a marine origin, gypsum, chert, sandstone rock fragments and the pervasive detrital calcite cement coating all sand grains. It is the detrital calcite cement which demonstrates that the grains are multicyclic in origin.

Mineral assemblages signifying a plutonic source terrain include quartz, feldspar (microcline, orthoclase), plagioclase (oligoclase), plutonic rock fragments, mica (muscovite, biotite), magnetite and zircon. Because these grains are coated by a detrital calcite cement, their plutonic heritage is considered ultimate with the proximate source interpreted as sedimentary.

Sample SA-2:

A bimodal, moderately well-sorted, subrounded, buff-colored *sand* collected from northeast Saudi Arabia, south of Tap Line Road. The two grain size modes consist of very coarse- (1.51 mm) and medium-sized (0.27 mm) grains.

Sample composition consists of 79% quartz, 6% potassic feldspar (microcline, orthoclase, perthite), 1% twinned plagioclase (oligoclase), 6% carbonate rock fragments, 3% plutonic rock fragments (quartz/orthoclase, plagioclase/orthoclase, microcline/plagioclase/muscovite), 5% volcanic rock fragments (rhyolite), < 1% mica (muscovite, biotite) and < 1% gypsum. This classifies the sample as a bimodal *sublithic quartz arenite*.

The lithic population (sedimentary, plutonic and volcanic grains) demonstrates a mixed parentage for the sand. The coarse-sized grains consist of quartz and volcanic rock fragments, which suggests a nearby igneous source terrain since volcanic rock fragments are considered labile and unable to survive great distances of transport intact.

The carbonate and plutonic rock fragments indicate a sedimentary and plutonic input into the basin. The presence of a detrital micrite (carbonate mud) cement coating each grain, reworked quartz overgrowths and the subrounded shape of the grains reveals that the grains are multicyclic with the most recent (proximate) source being sedimentary.

Sample SA-4:

A moderately sorted, subrounded, buff-colored, medium-grained (0.33 mm) *sand* collected from northeast Saudi Arabia, south of Tap Line Road. All grains are coated with a detrital micritic (carbonate mud) cement.

Sample composition consists of 79% quartz, 4% potassic feldspar (orthoclase, microcline), 1% twinned plagioclase, 7% carbonate rock fragments (micritic to microspar), 7% plutonic rock fragments (quartz/hornblende, quartz/plagioclase, quartz/muscovite, orthoclase/plagioclase), 1% volcanic rock fragments (rhyolite), 1% metamorphic rock fragments and < 1% heavy minerals (hornblende, hematite, zircon). This classifies the sample as a *sublithic quartz arenite*.

The presence of a thin micrite (carbonate mud) cement coating grains, the reworked quartz overgrowths (silica cement), the subrounded shape of the grains and an abundance of quartz (79%) indicates that the sand is multicyclic in origin and was most recently sourced by a sedimentary terrain. The carbonate rock fragments also imply a sedimentary parentage. Prior to being eroded and deposited as a sediment, the plutonic, metamorphic and volcanic rock fragments, feldspar/plagioclase population, heavy minerals and quartz were sourced by a mixed igneous (plutonic & volcanic) and metamorphic terrain.

Sample SA-5:

A poorly sorted, subrounded, medium-grained (0.33 mm), light buff- colored *sand* collected from northeast Saudi Arabia, south of Tap Line Road. The poor sorting is due to a range in grain size from clay ($<0.02\ \mu$) to coarse sand.

Sample composition consists of 60% siliciclastics (quartz with minor feldspar/plagioclase, plutonic & volcanic rock fragments) and 40% carbonate rock fragments, which classifies it as a *carbonate lithic quartz arenite*. The carbonate lithics include micrite (carbonate mud), concentrically laminated oöids (spar to detrital quartz nuclei) and fossiliferous micritic carbonates (bryozoan & unidentified plant fragments).

The 40% carbonate lithic population in this sand (80% micritic carbonate rock fragments, 10% oöids, 10% fossiliferous micritic rock fragments) is of a marine origin. Bryozoan fragments (marine invertebrate with calcareous skeleton) and oöids are diagnostic of a marine setting. Oöids (concentrically laminated grains) form in a shallow marine setting by grains being rolled in an oscillatory fashion (wave action) with a resultant concentric buildup of micrite (carbonate mud). The abundance of carbonate rock fragments and their labile nature (easily pulverized to clay-sized fraction) indicates a localized marine carbonate source for these lithics. The siliciclastics (60%) represent a mixture of multicyclic grains with an ultimate plutonic/volcanic source terrain.

Sample SA-6:

A bimodal, moderately sorted (each mode), subrounded, buff-colored *sand* collected from northeast Saudi Arabia, south of Tap Line Road. The bimodal grain size consists of very coarse- (1.50 mm) and medium-sized (0.33 mm) grains.

Sample mineralogy consists of 61% quartz, 5% potassic feldspar (orthoclase, microcline), <1% twinned plagioclase, 25% carbonate rock fragments (micritic to silty micritic), <1% sedimentary rock fragment (fossiliferous chert/sponge spicules), 3% metamorphic rock fragments (metaquartzite, epidote/ plagioclase), 2% plutonic rock fragments (polycrystalline quartz/biotite, quartz/plagioclase), 4% volcanic rock fragments (rhyolite) and <1% mica (biotite). This sample is classified as a *carbonate lithic quartz arenite*.

The strong carbonate rock fragment population (25%) and fossiliferous chert containing sponge spicules indicates a localized sedimentary source for the grains, most likely of a marine origin. Some of the rock fragments show replacement of calcite ($CaCO_3$) by gypsum ($CaSO_4 2H_2 0$), a common diagenetic process in marine sediments. The high percentage of labile sedimentary lithics suggests a localized source for the carbonate rock fragments.

The subrounded quartz and reworked quartz overgrowths indicate that the siliciclastic grains are multicyclic. The plutonic, metamorphic and volcanic rock fragments demonstrate an ultimate source terrain of mixed heritage.

Sample SA-7:

A bimodal, moderately sorted (each mode), subrounded, light brown *sand* collected from northeast Saudi Arabia, south of Tap Line Road. The bimodal grain size population consists of very coarse- (1.75 mm) and medium-size (0.35 mm) grains. The composition of this sand comprises 50% quartz, 10% potassic feldspar (orthoclase), < 1% twinned plagioclase (oligoclase), 30% carbonate rock fragments, 3% chertified carbonate rock fragments, < 1% metamorphic rock fragments (metaquartzite, epidote/plagioclase), 5% plutonic rock fragments (quartz/plagioclase/biotite, quartz/biotite, quartz/orthoclase), and 2% heavy minerals (hornblende, zircon, tourmaline). This sand is classified as a *carbonate lithic quartz arenite*. The carbonate lithics consist of silty to sandy micritic (carbonate clay) rock fragments.

This sand has an ultimate source of metamorphic and plutonic terrain. Reworked quartz overgrowths, detrital calcite (micritic) cement and subrounded grains indicate more than one sedimentary cycle for this sand. A localized sandy to silty carbonate terrain undergoing erosion is suggested as the source of the sand in this sample. The very coarse-sized quartz and plutonic rock fragments indicate a proximal igneous source.

Sample SA-8:

A bimodal, moderately sorted (each mode), buff-colored *sand* collected from northeast Saudi Arabia, south of Tap Line Road. The bimodal texture consists of very coarse- (1.10 mm) and medium-sized (0.40 mm) grains. The sand composition of this sample consists of 50% quartz, 7% potassic feldspar (orthoclase, microcline), 1% twinned plagioclase (oligoclase), 33% calcite rock fragments, 3% chertified silty carbonate rock fragments, < 1% metamorphic rock fragments (metaquartzite), 6% plutonic rock fragments (quartz/muscovite, untwinned plagioclase/mica, quartz/untwinned plagioclase), < 1% mica (chlorite, biotite) and < 1% hornblende, which classifies the sediment as a *carbonate lithic quartz arenite*. The carbonate lithics consist of micritic to sparry (coarsely crystalline) calcite and are the source of the clay-sized particles.

This sample displays a mixed-source parentage. Ultimate sources of the grains include plutonic (quartz, plutonic rock fragments, feldspar/plagioclase, mica, hornblende) and metamorphic (metaquartzite) terrains. The micritic to sparry carbonate rock fragments, quartz, reworked quartz overgrowths, and detrital micrite cement coating the siliciclastic grains attest to a reworked multicyclic sedimentary source.

Sample SA-9:

This sample is a medium-grained (0.35 mm), well-sorted, subrounded, light orange *sand*. It is a dune sand collected from near Riyadh. The sample contains 90% quartz, < 1% potassic feldspar (orthoclase), 6% micritic (carbonate mud) rock fragments, 2% sandstone rock fragments, 2% plutonic rock fragments (plagioclase/mica, quartz/hornblende) and < 1% hematitic oöids. The sediment is classified as a *quartz arenite*.

This sample is quartz rich (90%) and suggests a strong sedimentary parentage. Subrounded grains, reworked quartz overgrowths, detrital hematitic calcite cement coating the siliciclastic grains, carbonate (micritic) rock fragments and sandstone rock fragments all point to a sedimentary source terrain. The minor amounts of feldspar and plutonic rock fragments suggest an ultimate igneous source and attest to the compositional and textural maturity a sand can reach in an eolian dune environment.

Sample SA-10:

A poorly sorted, subrounded, buff-colored *sandy mud* (2/3 silt, 1/3 clay) collected from northeast Saudi Arabia, south of Tap Line Road. The composition consists of 30% siliciclastic grains (quartz, minor potassic feldspar/plagioclase) and 70% silty micritic rock fragments. This sediment is classified as a *sandy micritic mud* (2/3 silt, 1/3 clay).

In situ disaggregation of the silty micritic rock fragments forms the micritic mud. The siliciclastic grains are coated by a similar detrital micritic cement. This sandy micritic mud is directly sourced by the silty micritic rock fragments that it contains. The micritic rock fragments are, in turn, released from a nearby sedimentary source. The clasts are easily destroyed and are capable of only minimal transport.

Sample SA-11:

A very coarse-grained (1.43 mm), poorly sorted, subrounded, buff- colored, *clayey* (1/3 silt, 2/3 clay) *sand* collected from northeast Saudi Arabia, south of Tap Line Road. The composition consists of 5% quartz, 85% carbonate rock fragments (silty micritic to micritic) and 10% gypsiferous carbonate rock fragments, which classifies it as a *clayey carbonate lithic arenite*. The source of the clay-sized micrite is the *in situ* disaggregation of the carbonate rock fragments. This clayey sand was sourced by a localized carbonate sedimentary source terrain. The labile nature of the grains suggest that the source is proximal.

Discussion of Results

The samples range in grain size from granule (2.25-2.00 mm) to sand (1.75-0.27 mm) to silt (0.06-0.002 mm) to mud (2/3 silt, 1/3 clay) to clay ($<2\ \mu$). Grain size was dominated by the sand-sized fraction and a bimodal grain size distribution was present in 4 of the 11 samples analyzed. A bimodal distribution is believed to be attributed to the process of deflation/winnowing by the wind, which tends to concentrate the coarser grains as lag within the finer grained sediments.

Only two samples (SA-10, SA-11) contained appreciable amounts of mud (2/3 silt, 1/3 clay) and clay (<2 microns). In both instances, the clay-sized fraction is a carbonate mud. Petrographic examination reveals that the source of these clays is *in situ* disaggregation of micritic carbonate rock fragments.

The composition of the arenites indicate a mixed parentage. A plutonic source terrain is indicated by the presence of quartz, potassic feldspar (microcline, orthoclase, perthite), twinned plagioclase (oligoclase, labradorite), plutonic rock fragments (quartz/muscovite, quartz/orthoclase, quartz/ plagioclase, plagioclase/orthoclase, microcline/biotite/plagioclase/muscovite, quartz/hornblende, quartz/plagioclase/biotite, orthoclase/biotite, plagioclase/quartz/zircon, quartz/orthoclase/magnetite, plagioclase/myrmekite), mica (muscovite, biotite, chlorite) and heavy minerals (magnetite, zircon, tourmaline, rutile, hornblende, hematite).

Minerals indicating a metamorphic input to samples include clasts of metaquartzite, metaquartzite/epidote, plagioclase/epidote and gneiss. These rock fragments are diagnostic of low- to high-grade metamorphism. Volcanic input is shown by the presence of aphanitic rhyolite (phenocrysts of potassic feldspar/quartz/hematite) and basalt (phenocrysts of plagioclase/clinopyroxene/hematite, plagioclase/hematite, augite/oxyhornblende, plagioclase/magnetite).

Sample input was primarily sedimentary. Evidence for a sedimentary parentage includes detrital carbonate clay cement coating siliciclastic grains, reworked quartz overgrowths, carbonate rock fragments (micritic to microspar), sandstone rock fragments, chert and gypsiferous rock fragments. Carbonate clasts of marine origin include oöids, bryozoans, plant fragments and spicular chert. Fossilized carbonate rock fragments were documented in samples SA-5 and SA-6.

The siliciclastic grains in these samples are coated with a detrital carbonate mud cement. This is direct evidence of recycling, with sand-sized detritus being eroded from a sedimentary source rock. So although the ultimate source for the arenites involves a mixed heritage of plutonic, metamorphic and volcanic terrain, the most recent source is interpreted as sedimentary.

In terms of generalized provenance, the samples denote a mixed heritage of plutonic, metamorphic, volcanic (rhyolitic to basaltic) and marine carbonate terrain. All grains except the carbonates exhibit a multicyclic depositional history.

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